Direct Measurements of Absolute Branching Fractions for D^0 and D^+ Inclusive Semimuonic Decays

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By analyzing about 33 pb^{-1} data sample collected at and around 3.773 GeV with the BES-II detector at the BEPC collider, we directly measure the branching fractions for the neutral and charged D inclusive semimuonic decays to be $BF(D^0 \to \mu^+ X) = (6.8 \pm 1.5 \pm 0.7)\%$ and $BF(D^+ \to \mu^+ X) = (17.6 \pm 2.7 \pm 1.8)\%$, and determine the ratio of the two branching fractions to be $\frac{BF(D^+ \to \mu^+ X)}{BF(D^0 \to \mu^+ X)} = 2.59 \pm 0.70 \pm 0.25$.

I. INTRODUCTION

The neutral and charged D are both charmed mesons. However, the lifetime of the D^+ meson is surprised longer than that of the D^0 meson [1]. Isospin symmetry predicts that the partial widths to Cabibbo-favored semileptonic decays of the D^0 and D^+ mesons are equal. It is expected that the ratio of the branching fractions for the D^0 and D^+ inclusive semileptonic decays is approximately equal to the ratio of D^0 and D^+ lifetimes up to the order of $O(\theta_c^2)$ [2]. Measurements of the branching fractions for the D^0 and D^+ semileptonic decays can provide valuable information on the difference in their lifetimes, which is important to understand the charmed meson decays. Moreover, by comparing the branching fractions for the D^0 and D^+ inclusive decays with the sum of those for the exclusive decays, one can estimate whether there are some decay modes which are not observed yet. The D mesons inclusive semielectronic decays have been studied by several experiments [1, 3, 4]. However, the experimental studies for the D mesons inclusive semimuonic decays are very limited. Actually, there is no measurement for the decay $D^+ \to \mu^+ X$ available (X=any particles) in the PDG [1] now.

In this Letter, we report direct measurements of the absolute branching fractions for the inclusive decays $D^0 \to \mu^+ X$ and $D^+ \to \mu^+ X$, based on analyzing a data sample of about 33 pb^{-1} collected at and around the center-of-mass energy ($\sqrt{s}$) 3.773 GeV with the BES-II detector.

II. THE BEIJING SPECTROMETER

BESII is the upgraded version of the BES detector [5] operated at the Beijing Electron Positron Collider (BEPC) [6]. A 12-layer vertex chamber (VC) surrounding the beam pipe provides trigger information. A forty-layer main drift chamber (MDC) located outside the VC performs trajectory and ionization energy loss (dE/dx) measurement with a solid angle coverage of 85% of 4π for charged tracks. Momentum resolution of $\sigma_p/p = 1.7\%\sqrt{1+p^2}$ (p in GeV/c) and dE/dx resolution of 8.5% for Bhabha scattering electrons are obtained for the data taken at $\sqrt{s} = 3.773$ GeV. An array of 48 scintillation counters surrounds the MDC and measures the time of flight (TOF) of charged tracks with a resolution of about 200 ps for the electrons. Surrounding the TOF is a 12-radiation-length, lead-gas barrel shower counter (BSC) operated in limited streamer mode, which measures the energies of electrons and photons over 80% of the total solid angle, and has an energy resolution of $\sigma_E/E = 0.22/\sqrt{E}$ (E in GeV), spatial resolutions of $\sigma_\phi = 7.9$ mrad and $\sigma_Z = 2.3$ cm for the electrons. Outside of the BSC is a solenoidal magnet which provides a 0.4 T magnetic field in the central tracking region of the detector. Three double-layer muon counters instrument the magnet flux return, and serve to identify muon with momentum greater than 0.5 GeV/c. They cover 68% of the total solid angle with longitudinal (transverse) spatial resolution of 5 cm (3 cm). End-cap time-of-flight and shower counters extend coverage to the forward and backward regions. A Monte Carlo package based on GEANT3 has been developed for BESII detector simulation and comparisons with data show that the simulation is generally satisfactory [7].

III. DATA ANALYSIS

Around 3.773 GeV, the $\psi(3770)$ resonance is produced in electron-positron (e^+e^-) annihilation and decays into $D\bar{D}$ pairs with a large branching fraction, $BF(\psi(3770) \to D\bar{D}) = (85 \pm 5)\%$ [1, 8, 9, 10, 11]. If we can reconstruct $\bar{D}$ (they are named as singly tagged $\bar{D}$) from the $D\bar{D}$ pairs, the other D must exist on the recoil side of the tagged $\bar{D}$. Taking this advantage, we can directly measure the absolute branching fractions for the D decays with the singly tagged $\bar{D}$ samples. The singly tagged $\bar{D}$ samples used in the analysis were reconstructed from the hadronic decay modes of $mKn\pi$ (m=0,1, 2; n=0, 1, 2, 3, 4) in the previous works [12, 13]. These give the total numbers of $7584 \pm 198(\text{stat.}) \pm 341(\text{sys.})$ singly tagged $\bar{D}^0$ [12] and $5321 \pm 149(\text{stat.}) \pm 160(\text{sys.})$ singly tagged D^- [13]. Throughout the Letter, charge conjugation is implied.

A. Candidates for $D \to \mu^+ X$

The candidates for $D \to \mu^+ X$ are selected in the system recoiling against the singly tagged $\bar{D}$ mesons. It is required that the candidate tracks should be well reconstructed in the MDC with good helix fits, and satisfy $|\cos\theta| < 0.67$, where θ is the polar angle. Each track must originate from the interaction region, which requires that the closest approach to the interaction point in the xy-plane is less than 2.0 cm and in the z direction is less than 20.0 cm. To reject the muons from kaon and pion decays, the selected candidate tracks are required to originate from the same vertex as those decay from the singly tagged $\bar{D}$ mesons, by requiring $\delta z < 2\sigma_z$ (2.0 cm), where δz is the minimum distance in the z direction between the candidate track and those decay from the singly tagged $\bar{D}$, σ_z is the standard deviation of the δz distribution. To ensure that the track can be detected by the muon counter, the transverse momentum of each track is required to be greater than 0.52 GeV/c. Since the hit depth of muon in the muon counter varies with its transverse momentum, the muon is selected by requiring that the track should hit at least one layer for the track with the transverse momentum in the region (0.52, 0.75) GeV/c, two layers for the one in the region (0.75, 0.95) GeV/c, or three layers for the track with transverse momentum being greater than 0.95 GeV/c, respectively. Because there is no charge symmetric background as those in the measurements of the semielectronic decay [3, 4],

only "right-sign" muon candidates (with their charge opposite to the flavor of the single tag) are selected.

Fig. 1 shows the resulting invariant mass spectra of the $mKn\pi$ combinations for the events in which the candidates for muon are observed on the recoil side of the $mKn\pi$ combinations for the singly tagged $\bar{D}^0$ (left column) and D^- (right column) mesons. Fitting each invariant mass spectrum with a Gaussian function for $\bar{D}$ signal and a special function [12] to describe the background shape, we obtain number $N^{\mu}_{\rm obs}$ of the observed muon candidates. The total numbers of the observed candidates for $D^0 \to \mu^+ X$ and $D^+ \to \mu^+ X$ are 79.3 ± 10.3 and 99.6 ± 11.7, respectively.

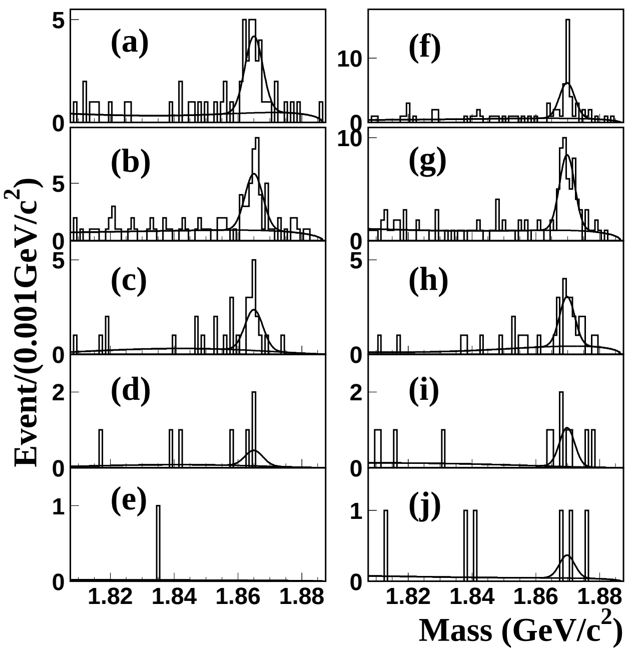

FIG. 1: Invariant mass spectra of the $mKn\pi$ combinations for the events in which the muon candidates are observed on the recoil side against the $mKn\pi$ combinations for the singly tagged $\bar{D}^0$ (left column) and D^- (right column) mesons, where the tracks are with the transverse momenta in the region: (a) and (f) (0.52, 0.62) GeV/c; (b) and (g) (0.62, 0.72) GeV/c; (c) and (h) (0.72, 0.82) GeV/c; (d) and (i) (0.82, 0.92) GeV/c and (e) and (j) (0.92, 1.02) GeV/c intervals, respectively.

B. Unfolding Procedure

Since the muon, electron, kaon and pion may be misidentified to each other, the observed muon candidates consist of the true muons and those are misidentified from electron, kaon and pion. The true yield $N^{\mu}_{\rm true}$ of muons can be extracted through an unfolding procedure. A detailed description of the unfolding procedure can be found in Ref. [4]. The right-sign candidates are unfolded using the matrix Eq. 1,

$$\begin{pmatrix} N^{\mu}_{\rm obs} \\ N^{e}_{\rm obs} \\ N^{K}_{\rm obs} \\ N^{\pi}_{\rm obs} \end{pmatrix} = \begin{pmatrix} \eta^{\mu\to\mu} & \eta^{e\to\mu} & \eta^{K\to\mu} & \eta^{\pi\to\mu} \\ \eta^{\mu\to e} & \eta^{e\to e} & \eta^{K\to e} & \eta^{\pi\to e} \\ \eta^{\mu\to K} & \eta^{e\to K} & \eta^{K\to K} & \eta^{\pi\to K} \\ \eta^{\mu\to\pi} & \eta^{e\to\pi} & \eta^{K\to\pi} & \eta^{\pi\to\pi} \end{pmatrix} \begin{pmatrix} N^{\mu}_{\rm true} \\ N^{e}_{\rm true} \\ N^{K}_{\rm true} \\ N^{\pi}_{\rm true} \end{pmatrix}, \tag{1}$$

where $N^{a}_{\rm obs}$ and $N^{a}_{\rm true}$ (a and b denote muon, electron, kaon or pion) are the number of the observed candidates for a and the number of the true a particles, respectively; $\eta^{b\to a}$ is the rate of misidentifying the particle b as a ($a \neq b$) or the efficiency of identifying the particle a ($a = b$).

To remove the misidentified particles from the observed muon candidate sample, we need to know the numbers $N^{e}_{\rm obs}$, $N^{K}_{\rm obs}$ and $N^{\pi}_{\rm obs}$ of electrons, kaons and pions besides the number $N^{\mu}_{\rm obs}$ of muons. They are also selected in the system recoiling against the singly tagged $\bar{D}$ mesons. Electron, kaon and pion are identified by using the dE/dx, TOF and BSC measurements, with which the combined confidence levels for the electron, kaon and pion hypotheses (CL_e, CL_K and CL_π) are calculated. An electron candidate is required to have $CL_e > 0.1\%$ and $CL_e/(CL_e + CL_K + CL_\pi) > 0.8$, and a kaon candidate is required to satisfy $CL_K > CL_\pi$ and $CL_K > 0.1\%$. The tracks not satisfying the selection criteria of muon, electron and kaon are treated as pions.

To obtain the number of the true muons, we also need to estimate the rates $\eta^{b\to a}$ by analyzing pure muon, electron, kaon and pion samples. The muon sample is selected from cosmic rays. The electron sample is selected from the radiative Bhabha events. The pion and kaon samples are selected from the $J/\psi \to \omega\pi^+\pi^-$ and $J/\psi \to \phi K^+K^-$ events, respectively. The difference between the $D\bar{D}$ decay event environment and the selected particle sample environment is studied with two Monte Carlo matrices. One matrix is determined using the muons. electrons, kaons and pions from the Monte Carlo simulated cosmic ray, Bhabha. $J/\psi \to \phi K^+K^-$ and $J/\psi \to \omega\pi^+\pi^-$ decays, and another matrix is produced using the particles from the $D\bar{D}$ Monte Carlo samples. The difference in the unfold yields with various matrices are about 3.9% for D^0 decay and 2.1% for D^+ decay. Since the rates $\eta^{b\to a}$ vary with momenta of the particles, we divide the transverse momentum region (0.52,1.02) GeV/c into five intervals in the analysis. Figure 2 shows the rates $\eta^{b\to a}$ in each transverse momentum interval obtained from the pure particle samples.

Inserting the numbers of $N^{a,i}_{\rm obs}$, the rates $\eta^{b\to a,i}$ (i denotes the ith transverse momentum interval) in the matrix Eq. 1, we obtain the yield $N^{\mu,i}_{\rm true}$ of the true muons in the ith momentum interval. Summing the $N^{\mu,i}_{\rm true}$ over the intervals, gives the total numbers of the true yield candidates to be 87.5 ± 17.1 for $D^0 \to \mu^+ X$ and 129.3 ± 19.5 for $D^+ \to \mu^+ X$, respectively.

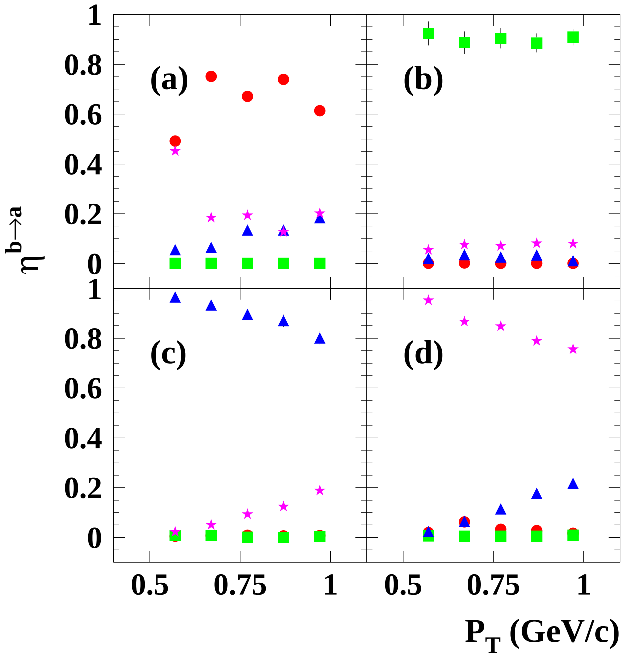

FIG. 2: $\eta^{b\to a}$ (a and b denote muon, electron, kaon or pion) are the rates of misidentifying the particle b as a ($a \neq b$) or the efficiency of identifying the particle a ($a = b$), where the dots, squares, triangles and stars are for the particles (mis)identified as muon, electron, kaon and pion from the pure particle samples: (a) the muon sample selected from the cosmic rays; (b) the electron sample; (c) the kaon sample and (d) the pion sample.

C. Other Background

In the selected candidate events, there are still some contaminations from decays $K^+ \to \mu^+\nu_\mu$ and $\pi^+ \to \mu^+\nu_\mu$. These backgrounds are estimated based on the Monte Carlo simulation. The simulated background events are generated as $e^+e^- \to D\bar{D}$ events, where D and $\bar{D}$ mesons are set to decay into all possible modes except $D^0 \to \mu^+X$ for studying the D^0 decay, or except $D^+ \to \mu^+X$ for studying the D^+ decay, respectively. In the Monte Carlo simulation, the decay modes of D mesons and their branching fractions are quoted from PDG [1], and the particle trajectories are simulated with the GEANT3 based Monte Carlo simulation package of the BES-II detector [7]. The numbers of these background events are estimated to be 8.4 ± 1.8 and 3.0 ± 1.6 for $D^0 \to \mu^+X$ and $D^+ \to \mu^+X$, respectively. After subtracting these background events, we obtain 79.1 ± 17.2 and 126.3 ± 19.6 signal events for $D^0 \to \mu^+X$ and $D^+ \to \mu^+X$, respectively.

IV. RESULTS

The branching fraction for $D \to \mu^+X$ is determined by

$$BF(D \to \mu^+X) = \frac{N_{D\to\mu^+X}}{N_{\bar{D}} \times \epsilon_{D\to\mu^+X}}, \qquad (2)$$

where $N_{D\to\mu^+X}$ is the number of the events for $D \to \mu^+X$, $N_{\bar{D}}$ is the number of the singly tagged $\bar{D}$ mesons, $\epsilon_{D\to\mu^+X}$ is the detection efficiency for $D \to \mu^+X$.

The detection efficiency $\epsilon_{D\to\mu^+X}$ is estimated with the Monte Carlo simulation. The Monte Carlo events are generated as $e^+e^- \to D\bar{D}$, where $\bar{D}$ decay into the singly tagged $\bar{D}$ modes and D decay into semimuonic modes. The semileptonic decays are generated with the q^2 dependence of form factors given by the pole model [14]. The generator has been applied in the previous measurements and reproduces exclusive semileptonic spectra well [15, 16, 17, 18, 19]. In order to study the model dependence of the efficiency, the semileptonic decays are also simulated with the ISGW2 form factor model [20]. The difference in efficiencies determined with various form factor models is about 5.8%. The averaged efficiency is determined by weighting the branching fractions of the D meson semimuonic decays [1] and the numbers of the singly tagged $\bar{D}$ events. The efficiencies are $(15.4 \pm 0.2)\%$ for $D^0 \to \mu^+X$ and $(13.5 \pm 0.2)\%$ for $D^+ \to \mu^+X$, respectively.

Inserting the number $N_{D\to\mu^+X}$ of the signal events for $D \to \mu^+X$, the number $N_{\bar{D}}$ of the singly tagged $\bar{D}$ mesons and the detection efficiency $\epsilon_{D\to\mu^+X}$ in Eq. (2), we obtain the branching fractions for $D \to \mu^+X$ to be

$$BF(D^0 \to \mu^+X) = (6.8 \pm 1.5 \pm 0.7)\%$$

and

$$BF(D^+ \to \mu^+X) = (17.6 \pm 2.7 \pm 1.8)\%,$$

where the first errors are statistical and the second systematic.

The systematic errors arise mainly from the uncertainties in particle identification ($\sim 5\%$ for muon [21]), in tracking ($\sim 2.0\%$ per track), in the number of the singly tagged $\bar{D}$ mesons ($\sim 4.5\%$ for $\bar{D}^0$ [12] and $\sim 3.0\%$ for D^- [13]), in the δz selection criterion ($\sim 3.5\%$), in the input form factor models ($\sim 5.8\%$), in the selected sample environment ($\sim 3.9\%$ for D^0 and 2.1% for D^+), and in the Monte Carlo sample statistics ($\sim 1.5\%$). The systematic errors from the uncertainties of the $\eta^{b\to a}$ in the unfolding procedure are estimated using the Monte Carlo samples generated with the Gaussian distribution to describe the uncertainties of the $\eta^{b\to a}$ matrices, and they are estimated to be $\sim 2.1\%$ for D^0 and $\sim 1.0\%$ for D^+, respectively. The systematic errors from the poorly measured exclusive semileptonic decay modes are estimated using $D\bar{D}$ Monte Carlo samples generated with or without those modes, they are about 3.3% and 4.7%

for $D^0 \to \mu^+\nu_\mu$ and $D^+ \to \mu^+\nu_\mu$, respectively. Adding these uncertainties in quadrature yields the total systematic errors to be 11.0% and 10.3% for $D^0 \to \mu^+X$ and $D^+ \to \mu^+X$, respectively.

With the measured branching fractions for $D^0 \to \mu^+X$ and $D^+ \to \mu^+X$, the ratio of the two branching fractions is determined to be

$$\frac{BF(D^+ \to \mu^+X)}{BF(D^0 \to \mu^+X)} = 2.59 \pm 0.70 \pm 0.25,$$

where the first error is statistical and the second systematic arising from the uncertainties in the number of the singly tagged $\bar{D}$ mesons, in the $\eta^{b\to a}$, in the Monte Carlo sample statistics, in the the selected sample environment and in the poorly measured decay modes.

Table I shows the comparisons of the measured branching fractions for $D \to \mu^+X$ by the BES Collaboration with those measured by the ARGUS [22], CHORUS [23] Collaborations and the averaged value from PDG [1]. The measured $BF(D^0 \to \mu^+X)$ is in good agreement with the measurements from other Collaborations.

V. SUMMARY

Using the data sample of about 33 pb^{-1} collected at and around $\sqrt{s} = 3.773$ GeV with the BES-II detector at the BEPC collider, we have studied the inclusive semimuonic decays of D mesons. The absolute branching fractions for $D^0 \to \mu^+X$ and $D^+ \to \mu^+X$ are measured to be $BF(D^0 \to \mu^+X) = (6.8 \pm 1.5 \pm 0.7)\%$ and $BF(D^+ \to \mu^+X) = (17.6 \pm 2.7 \pm 1.8)\%$. The latter one is the first measurement. With the measured branching fractions for $D^0 \to \mu^+X$ and $D^+ \to \mu^+X$, the ratio of the two branching fractions is determined to be $BF(D^+ \to \mu^+X)/BF(D^0 \to \mu^+X) = 2.59 \pm 0.70 \pm 0.25$, which is consistent with the ratio of the lifetimes of D^+ and D^0 mesons, $\tau_{D^+}/\tau_{D^0} = 2.54 \pm 0.02$ [1].

VI. ACKNOWLEDGMENTS

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TABLE I: Comparisons of the measured branching fractions for the inclusive semimuonic decays of D mesons with those measured by ARGUS [22], CHORUS [23] Collaborations and the PDG values [1].

	BES	ARGUS	CHORUS	PDG06
$BF(D^0 \to \mu^+ X)[\%]$	6.8±1.5±0.7	6.0±0.7±1.2	6.5±1.2±0.3	6.5±0.7
$BF(D^+ \to \mu^+ X)[\%]$	17.6±2.7±1.8	-	-	-
$\frac{BF(D^+ \to \mu^+ X)}{BF(D^0 \to \mu^+ X)}$	2.59±0.70±0.25	-	-	-
$\frac{\tau_{D^+}}{\tau_{D^0}}$	-	-	-	2.54±0.02